BAKSAN NEUTRALINO SEARCH

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A search for signal from neutralino annihilation in the Earth's core and in the Sun is performed using sample of 558 upward-going events collected by Baksan Underground Scintillator Telescope during 11.94 years of live time.

In previous note [1] we reported upper limits on flux of upward-going muons from the Sun and from the Earth's core obtained within the angular window of 30° for dark matter search. Here we present new detailed angular analysis of update sample of 558 events which is used in a search for possible signals of high energy neutrino originated from annihilation of massive neutralinos in the core of the Earth and the Sun.

1 Experiment

Baksan Underground Scintillator Telescope is located in underground laboratory at the effective depth of $850hg/cm^2$ (43°16′N and 42°41′E). Detector itself is a parallelepiped ($17m \times 17m \times 11m$) and consists of 3,150 liquid scintillator counters of standard type ($70cm \times 70cm \times 30cm$), which entirely cover all sides of parallelepiped and two horizontal planes inside at the distances 3.6 m and 7.2 m from the bottom. So, telescope has four vertical and four horizontal planes. Each plane is separated from another one by concrete absorber of $160g/cm^2$. The particles trajectory is reconstructed by the positions of hit tanks and the arrival direction is determined by measurements of $1/\beta$, so that a positive value is expected for downward-going muons and a negative value is expected for upward-going particles. The time resolution of the telescope, measured with downward-going muons, is equal to 5 ns. Averaged accuracy of angle reconstruction is better than 2°.

Two hardware triggers being used to select upward-going muons (for more details see ref. [2]) reduce initial rate of downward-going muons by factor $\approx 10^3$, while expected ratio of flux of downward-going muons to upward-going one is about 10^7. Trigger 1 covers the zenith angle range $95° \div 180°$ while trigger

2 selects horizontal muons in the range $80° \div 100°$. The hardware trigger efficiency of 99% has been measured with the flux of atmospheric muons. These two triggers give about 1,800 events per day for further processing.

An off-line program reconstructs events and selects those of them which satisfy two simple requirements: only one trajectory of penetrating particle and negative measured value of $1/\beta$. However all events with negative values of $1/\beta$ have been scanned by eye to check possible misinterpretation and there were no observed events within range of $-0.5 \leq 1/\beta \leq 0$.

The data used for this analysis have been collected from December of 1978 until June of 1995, with 11.94 live-years. It was found that 840 events survived these cuts.

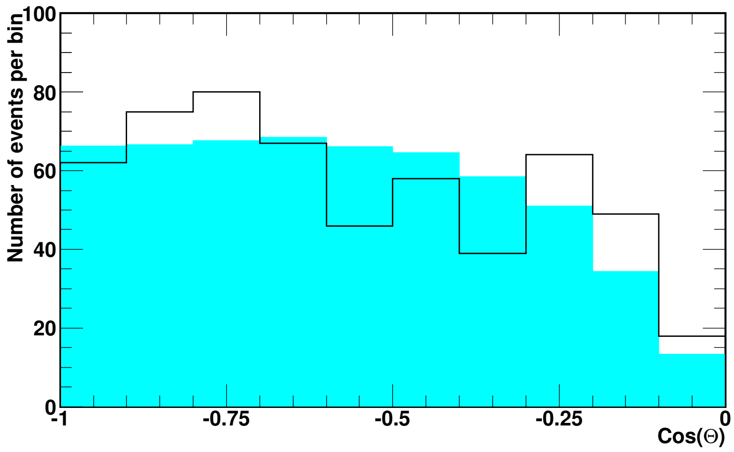

Figure 1: Distribution in $\cos(\theta)$ for upward-going muons observed with the Baksan Underground Scintillator Telescope. The shaded histogram is Monte Carlo simulations.

Additional cuts have been applied in order to reject upward-going trajectories that could be mimicked by downward-going atmospheric muon interactions or multiple muons. They are: i) the muon trajectory must have entry and exit points (stopping muons and neutrino interactions inside the detector are excluded), and ii) muon range inside detector must be $500 g/cm^2$ or more. These criteria cut off particles with energy below $\approx 1 GeV$. Also, for trajectories crossing only two scintillator planes (trigger 2) we have excluded tracks having azimuthal angles $180° \leq \phi \leq 360°$ (direction of minimum shallow depth) as well as events with entry or exit points closer than 1.5m to the plane edge. Finally, the events with $1/\beta$ in the range of $-1.3 \div -0.7$ have been accepted.

(The distribution in $1/\beta$ measured with downward-going single muons shows that 95% of all events are in the range of $0.7 \div 1.3$.) In total 558 events survived all cuts. In Fig.1 solid histogram shows the zenith angular distribution of these events.

The shaded histogram in Fig.1 is a result of complete Monte Carlo simulations of upward through-going muons induced by atmospheric neutrinos. In calculations we have used the latest calculations of atmospheric neutrino flux [3] and the conventional expression for the cross-section of neutrino charged current deep-inelastic scattering off isoscalar targets. The structure functions F_2 and xF_3 have been calculated with parton density distributions given in ref. [4]. The muon propagation has been simulated for Baksan rock using the energy-loss parameterization given by Lohman et. al [5]. We have generated in total of 273184 neutrino interactions in surrounding rock. It corresponds to 100 runs of real data taking.

The simulations of detector response have been done with the same requirements for hardware triggers and the same set of cuts as for real data. The spread in setting of thresholds ($\approx 10\%$), PMT's gain ($\approx 10\%$), and time off-set of PMT's ($\approx 2ns$) as well as dead tanks ($\approx 1\%$) have been taken into account. The hardware triggers were produced for 29% of events. Finally we have found of 55692 generated events that survived all cuts. The comparison of observed and simulated distributions in number of hitted tanks as well as in thickness of absorber crossed by trajectories shows good agreement.

The ratio of observer number of events to expected one is found to be $1.00 \pm 0.04(stat.) \pm 0.08(syst.) \pm 0.15(theor.)$. The systematic uncertainties have been evaluated varying detector parameters relevant to the observation of upward-going particles. The theoretical uncertainties of 15% are mainly due to the absolute normalization of the atmospheric neutrino flux.

As far as events coming from near the core of the Earth and the Sun are studied as a possible high energy neutrino signal from dark matter annihilation, in Fig.2 we present the angular distributions of number of observed events (solid histogram) in direction of the Earth's core and Sun in comparison with expected one from atmospheric neutrinos (shaded histograms). In the case of the Earth's core expected histogram has been obtained in same way as in Fig.1, and in the case of the Sun background has been evaluated from data itself, considering fake "Suns" which have the same acceptance as true Sun but shifted at some hour angle.

Since the observed distributions are consistent with expected from atmospheric neutrinos, the upper limits on number of upward-going muons from the direction of the Earth's core and the Sun can be obtained. Dash-dotted histograms in Fig.2 show upper limit at the 90% c.l. as a function of size of angular window.

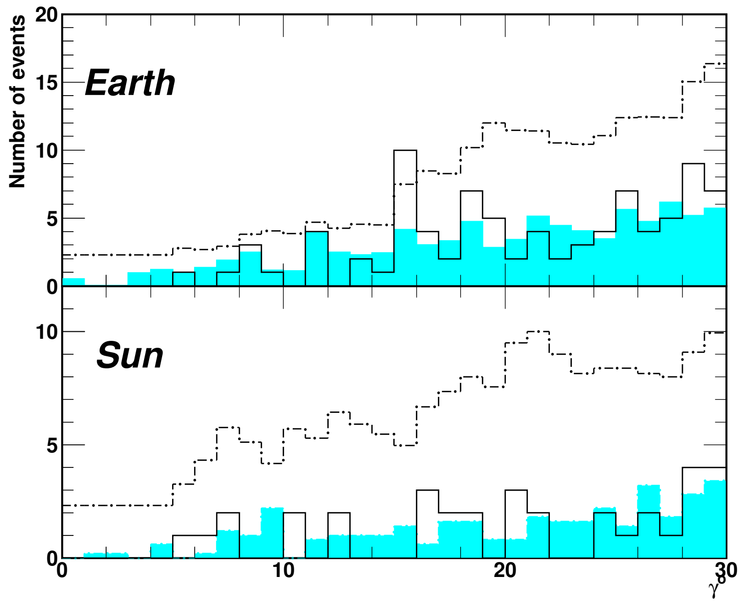

Figure 2: Distribution in γ for upward-going muons from directions of the Earth's core and the Sun. Solid histogram is data and shaded one is expectation for atmospheric neutrinos. Dash-dotted histogram is upper limits at 90% c.l. on number of upward-going muons produced by neutrinos nonatmospherc origin as a function of cone opening angle γ.

2 Upper limits in neutralino search

Usually experimental results of indirect neutralino search are presented in terms of limits on muon flux induced by neutrinos from neutralino annihilation. On our opinion for the purpose of comparison with model prediction limits on annihilation rate Γ_A are more adequate. Indeed, an upper limit on annihilation rate can be written as

$$\Gamma_A = \frac{N_{90\%c.l.}(\gamma)}{T \cdot \varepsilon_\gamma} \times \frac{1}{W}, \tag{1}$$

where $N_{90\%c.l.}(\gamma)$ is 90% c.l. experimental limit on number of events for given angular window γ, T is time of observation, and ε_γ is a fraction of total number of events containing within of angular window γ. In our analysis we have used $\varepsilon_\gamma = 0.9$. The term W is probability to detect muon per one neutralino - antineutralino annihilation. It absorbs neutrino spectra, neutrino interactions, propagation of produced muons, and detector response. With this

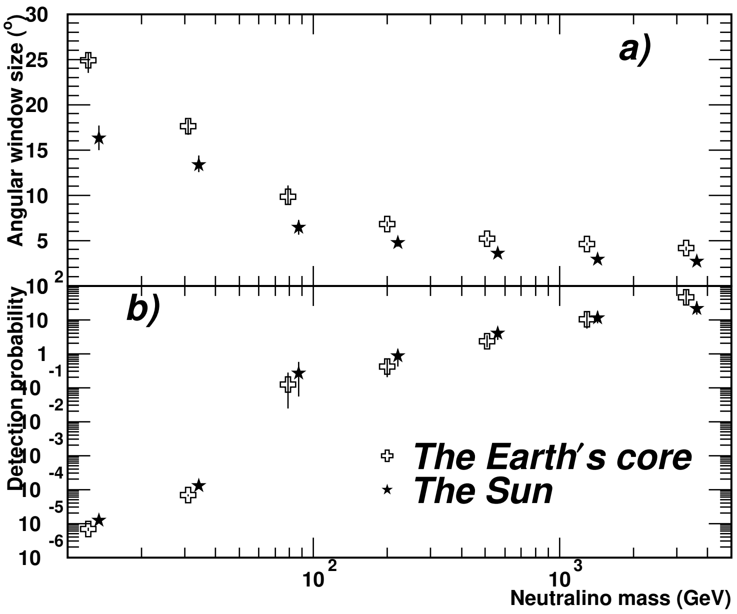

Figure 3: The dependance on neutralino mass of size of angular window (a) and probability of detection of single neutralino annihilation (b) multiplied by factor 10^{20} (10^{29}) for the case of the Earth's core (the Sun). Vertical bars show spread due to variations of another model parameters.

definition limit on Γ_A is completely detector independent while limit on muon flux depends on detector energy threshold, which is not always well defined.

We have extensively studied the detection probability W using the same Monte Carlo generator as above, except neutrino spectrum from neutralino annihilation has been inserted into generator. In Fig.3 we show the size of angular angular window and detection probability as a function of neutralino mass. In our analysis we have used phenomenological approch to MSSM, considering only four free parameters: $\tan\beta$, mass of pseudo-scalar Higgs boson m_A, neutralino mass m_χ, and gaugino fraction of neutralino P. (The pair of variables m_χ and P is equivalent to usual pair of parameters M_2 and μ, due to one to one mapping). We have also assumed sfermion masses to be infinite and have taken into account one-loop radiative correction to Higgs boson masses.

We considered all final states in neutralino annihilation. To calculate differential neutrino spectra from annihilation to fermion pairs the same approach as in ref. [6] with parameterization given by Kamiokande group [7] was used. In

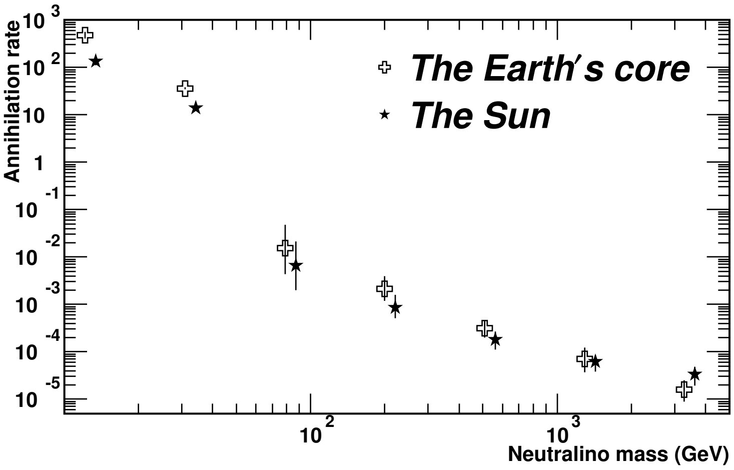

Figure 4: Upper limits at 90% confidence level on annihilation rate in units of $10^{15}s^{-1}$ ($10^{24}s^{-1}$) for the Earth's core (crosses) (the Sun (stars)) as a function of neutralino mass. Vertical bars show spread due to variations of another model parameters.

the case of neutralino annihilation inside the Sun we have used explicit expression [8] for neutrino propagation through solar matter. And we took into account neutrino angular distribution due to neutralino space spread inside of the Earth's. We varied model parameters in the following ranges: $\tan\beta = (2 \div 32)$, mass of pseudo-scalar Higgs boson $m_A = (50 \div 10^3)GeV$, neutralino mass $m_\chi = (10 \div 5 \cdot 10^3)GeV$, and gaugino fraction of neutralino $P = (0.01 \div 0.99)$. For each set of parameters we generated 1000 events, that survived all experimental cuts, and evaluated size of angular window containing 90% of events and detection probability taking into account distance to neutrino source.

We have found, that in studied range of neutralino masses both size of angular window γ and detection probability W vary approximately within 30% with variation of another model parameters. It is due to the fact that values of W and γ are determined by the shape of neutrino spectrum, which is fixed mainly by value of neutralino mass. However around neutralino mass equals to mass of W-boson the spread of detection probability is much higher. Bars in fig.3 show spread in values of γ and W due to variation of model parameters. The upper limit on annihilation rate for several values of neutralino masses are shown in Fig.4 and Table 1. In Table 1 we show also limit on flux of muons with energy ¿ 1 GeV. Here, in order to derive limit we have used averaged value of γ and W for each neutralino mass.

Table 1: The size of angular windows and upper limits at 90% confidence level on annihilation rates and fluxes of upward-going muons for neutralino annihilation in the Earth's core and the Sun.

	Earth			Sun		
m_χ (GeV)	γ ($\circ$)	Γ_A s_{-1}	F_μ $cm^{-2}s^{-1}$	γ ($\circ$)	Γ_A s_{-1}	F_μ $cm^{-2}s^{-1}$
12.8	25	$4.8 \cdot 10^{17}$	$3.2 \cdot 10^{-14}$	16	$1.3 \cdot 10^{26}$	$2.4 \cdot 10^{-14}$
32.6	18	$3.6 \cdot 10^{16}$	$2.1 \cdot 10^{-14}$	13	$1.4 \cdot 10^{25}$	$2.1 \cdot 10^{-14}$
82.8	10	$1.5 \cdot 10^{13}$	$9.3 \cdot 10^{-15}$	6.5	$6.6 \cdot 10^{21}$	$1.1 \cdot 10^{-14}$
210.0	7.0	$2.1 \cdot 10^{12}$	$6.2 \cdot 10^{-15}$	4.7	$8.6 \cdot 10^{20}$	$6.5 \cdot 10^{-15}$
535.0	5.0	$3.1 \cdot 10^{11}$	$5.4 \cdot 10^{-15}$	3.6	$1.8 \cdot 10^{20}$	$6.4 \cdot 10^{-15}$
1358.0	4.5	$7.1 \cdot 10^{10}$	$5.2 \cdot 10^{-15}$	3.0	$6.2 \cdot 10^{19}$	$6.4 \cdot 10^{-15}$
3454.0	4.0	$1.6 \cdot 10^{10}$	$5.2 \cdot 10^{-15}$	2.7	$3.4 \cdot 10^{19}$	$6.4 \cdot 10^{-15}$

3 Conclusion

The comparison of experimental data with detail Monte Carlo simulations of expected signal from neutralino annihilation in the Earth's core and the Sun allows significantly improve the signal to background ratio. Baksan data don't show any excess of upward-going muons from the direction of the Sun and the Earth's core. We have got new upper limits at the 90% c.l. on annihilation rate inside these sources. We intend to continue this analysis for more detail study dependence of expected signal on all model parameters especially around neutralino masses equal to masses of gauge bosons and top quark.

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